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**CONCEPTUAL DESIGN OF A NEW DAMAGE
ASSESSMENT CAPABILITY**

Decision—Science Applications, Inc.
1500 Wilson Boulevard
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March 1978

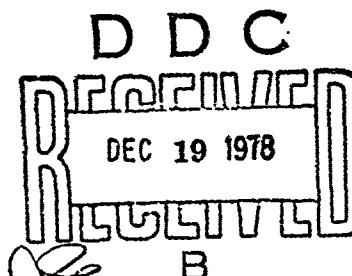
Final Report for Period 12 July 1977—31 March 1978

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20. ABSTRACT (Continued)

launch, etc., uncertainty in height of burst, population protection factors, and so on. All or any of these may be accommodated in a single run, since sampling over the uncertainty distributions, sampling over national wind patterns, sampling AGZs from other attack descriptions, and applying standard effects calculations to a set of population samples, is the basis of a modular calculation. With standard damage assessment systems, any attempt to cover such a range of variation would imply an explosive combinatorial growth in computation time.

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CONTENTS

<u>SECTION</u>		<u>PAGE</u>
1	EXECUTIVE SUMMARY	3
1.1	Introduction	3
1.2	Sources of Uncertainty Addressed	3
1.3	Computational Speed	5
1.4	Design Principles	5
1.5	Potential Applications	6
1.6	Development Risks and Costs	8
2	THE NEW DAMAGE ASSESSMENT SYSTEM	10
2.1	Overview	10
2.2	Basic Processing Logic	32
2.3	1st Processor: Weapons Effects Computation	32
2.4	2nd Processor: Population Response & Statistical Computation	35
2.5	Data Base Considerations	36
2.6	Recommendations	37
 <u>APPENDIX</u>		
A	STRATEGIC UNCERTAINTY	39

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1. EXECUTIVE SUMMARY

1.1 INTRODUCTION

The Defense Nuclear Agency has a responsibility to support other agencies in predicting the effects of nuclear weapons in a wide variety of operational contexts. In many of the present damage assessment applications there is a need, not just to predict probable outcomes, but to provide confidence information concerning the variability and uncertainty of the possible outcomes. Although existing damage assessment systems can provide estimates of the probable damage, when all relevant factors are known, they have little or no capability to deal with the variability and uncertainty of the predicted outcomes that must be considered in many practical applications.

This report describes the design concept for a new statistical damage assessment system capable of addressing the broad spectrum of uncertainties that are involved in the assessment of damage from nuclear strikes. The system can be used to assess the variability and uncertainty of outcomes not only from large scale nuclear strikes, but also from limited strategic strikes and various tactical applications of nuclear weapons. Thus it fills the need for an analytical tool capable of assessing the risks and uncertainties associated with both theater and strategic use of nuclear weapons.

1.2 SOURCES OF UNCERTAINTY ADDRESSED

The system is designed to provide an analysis of the uncertainty and variability associated with the full range of factors that are involved in a damage assessment calculation. The factors include:

1. Uncertainty about which of several alternative war plans may actually be implemented.

2. Uncertainty about the key planning factors such as:

- Yield
- Accuracy
- Height of burst
- System reliability
- Penetration probability
- Probability of destruction before launch

3. Uncertainty about the target environment

- Variability of fallout winds
- Geodetic error

4. Uncertainty about the target posture and vulnerability

- Target hardness
- Shelter posture of population
- Population location (evacuation)
- Actual target location

5. Uncertainty about weapons-effects models

- Fallout models
- Blast effect models
- Prompt radiation
- Thermal radiation, fire, etc., to the extent that models are available

6. Uncertainty about the interaction between different weapons effects

The structure of the system makes it possible to evaluate the variability and uncertainty in the damage assessment outcomes that are associated with the above sources of uncertainty. The extent of the uncertainty can be evaluated separately for each of the factors or for any combination of factors that may be of interest within a particular analysis.

1.3 COMPUTATIONAL SPEED

By using statistical sampling techniques to reduce the computational burden of damage assessment calculations, the system can provide information concerning the full statistical distribution of probable outcomes with about the same computational effort that is normally required to assess the outcome for a single set of assumptions.

The computational efficiency of the system makes it possible to use more detailed weapons-effects models and more accurate and complete damage assessment models than is now feasible in existing damage assessment systems. Consequently, the system can be used to compare the results from simplified weapons effects models with the results obtained from more detailed and presumably more accurate theoretical models. This capability of the system should assist DNA in meeting its obligation to evaluate or validate such operational models.

1.4 DESIGN PRINCIPLES

Most conventional damage assessment systems require substantial computer time just to evaluate the effects of a single attack for one set of conditions concerning the fallout winds and other environmental factors. The large running time results from the fact that the damage must be evaluated individually for every element of the target data base (taking into account the effects of all weapons that are included in the strike). For data bases that include upwards of a hundred thousand

separate elements such calculations can be very time consuming. If one were to attempt to use such a system to assess the uncertainty and variability of the damage, separate runs of this magnitude would be required for each set of assumptions concerning winds, weapons effects uncertainties, actual weapons delivered, and all the other uncertainty factors that might be considered. Thus the total running time for such an analysis could be prohibitive.

The design concept developed here uses statistical sampling techniques to minimize the number of target data elements that must be evaluated for each set of assumptions. This makes it possible to consider a much wider range of situations and uncertainty factors than would be feasible in a conventional analysis system. In actual operation the process of sampling the target data elements is carried out concurrently with a statistical sampling of the uncertainty factors. Techniques of statistical analysis are used so that the actual variability and uncertainty resulting from the real world uncertainty factors can be correctly evaluated, in effect by subtracting out the artificial uncertainty that results from the use of statistical sampling techniques.

1.5 POTENTIAL APPLICATIONS

1.5.1 Risk Evaluation of Strategic Strike Options

Strategic war planners normally go to great lengths to ensure that plans will not fail catastrophically even in the most unlikely contingencies. The problem is not to maximize the probable damage, but to devise strategies that will hedge effectively even against unlikely adverse contingencies. Nevertheless existing damage assessment systems are designed only to evaluate the most probable outcomes. There is a clear need for a damage assessment system that can display the statistical

range of possible outcomes. Such a system could serve a useful role in the evaluation of strategic warplans by validating the hedging strategies used in the plans.

1.5.2 Assessment of Collateral Damage from Limited Strikes

One of the most serious problems encountered with limited nuclear strike options concerns the risk that collateral damage to friendly troops or to unintended targets such as population may be much higher than expected. The system provides a capability to assess these risks quantitatively taking into account all the key uncertainties that may be involved. In the case of limited strikes involving small numbers of weapons, the system can be run using a very large statistical sample so that accurate risk statistics can be developed for all threatened areas of interest.

1.5.3 Assessment & Evaluation of Strategic Damage Estimates

There are a wide spectrum of views about the actual level of damage likely to result from large scale or limited nuclear strikes. Advocates of opposing political views tend to justify their arguments on the basis of uncertainties in damage estimates and by reference to a variety of weapons-effects which they claim are ignored in the standard calculations. The damage assessment concept suggested here can provide a quantitative tool for assessing the uncertainties and evaluating the impact of secondary effects that are usually ignored.

1.5.4 Provision of a Damage Assessment Standard

To achieve acceptable running times, conventional damage assessment systems make a number of compromises in computational procedures. Multiple target elements are lumped and treated as one even though they have slightly different locations and different vulnerabilities, and weapons effects models are simplified. The statistical sampling techniques used in the present design concept make it possible to carry out

the damage assessment calculations in as much detail and accuracy as is needed for each sample point. Thus the system can provide a standard of comparison that is as free as possible from systematic errors.

Conventional systems often disagree with each other in the estimated effects of a specific attack. The differences can often be traced to differences in the specific fallout winds that were used as the basis for calculations, or to differences in vulnerability assumptions, or in the way specific weapons effects are modeled. By providing an analysis not only of the probable outcome, but of the range or variability and uncertainty in the possible outcomes, a statistical system can be used to determine whether such differences are within the reasonable range of uncertainty and variability, or whether they are indicative of major flaws or errors in the calculations.

1.5.5 Evaluation of Simplified Models

In many analysis applications the running time that would be required for really accurate and detailed weapons effects models would be prohibitive. Thus there is a need for fast running simplified models that are sufficiently accurate for specific applications. DNA is often called upon to supply or validate such simplified models. The statistical damage assessment system can provide an environment in which the accuracy and range of validity of such models can be evaluated relative to more detailed models over a wide range of operational applications. Thus it provides a tool that should assist DNA in meeting its obligation to test and validate such models.

1.6 DEVELOPMENT RISKS AND COST

The statistical approach to damage assessment has been utilized on a limited basis in the past, particularly in the evaluation of alternative civil defense shelter postures. Consequently, the basic design principles are well understood and predictions of operational performance can be

made with considerable confidence on the basis of actual past experience. As a consequence of this earlier experience the development of a modern system of this type can be undertaken with minimal risk.

It is estimated that an operational system can be completed, documented and installed at several facilities within an eighteen month period. The total development cost is estimated at about \$300,000. To avoid duplication of previous work it is anticipated that the development will exploit both statistical methodology and relevant applicable computational subsystems that are available from earlier systems. The estimated labor required should total about four man years. However, because of the requirement to develop complex statistical analysis subsystems that interact with each other in a flexible and modular way, the development must be staffed with exceptionally competent personnel with a background in statistical inference, as well as in nuclear damage assessment and computer systems design.

2. THE NEW DAMAGE ASSESSMENT SYSTEM

2.1 OVERVIEW

The estimation of fatalities or industrial damage from nuclear attacks is a well established capability. The variability in these estimates remains an area of great uncertainty. The recent critical debate concerning U.S. civilian casualties from Soviet limited nuclear strikes against U.S. ICBM installations is a case in point. There is a clear need today for a damage assessment system capable of addressing the uncertainties in typical strategic calculations. The uncertainty or chance factors arise not only in the limitations imposed by the methods of calculation, but in the actual physical phenomenon being modeled. For example, for many types of attacks one of the most important uncertainties concerns the variability in fallout exposure due to wind patterns. This source of uncertainty is inherent in the phenomenon being modeled, and no perfection of mathematical modeling can reduce it. As a practical matter, many of the other uncertainties--such as population behavior in the face of an attack, and even the operational performance of weapon systems--entails unavoidable uncertainties. The proper function of a damage assessment system is not to artificially eliminate the uncertainties, but to provide the user with a realistic assessment of the impact of the uncertainties that arise as a consequence of factors such as:

- Variability due to the attack
- Variability due to the winds
- Variability due to evacuation effectiveness or sheltering posture.

This report proposes a new damage assessment system capable of producing not only correct values of average (expected) damage, but also variability of damage due to chance events such as weapon delivery probabilities, impact errors (CEP), height of burst uncertainty, and particularly (for fallout calculations) the variability of wind conditions.

Explicit treatment of the uncertainties in the population sheltering posture can also be directly addressed. This system is designed to make use of the most accurate and complete weapons effects models and to make use of the most detailed information on population location and protection postures. The fundamental feature which would distinguish this system from other current damage assessment systems is the application of statistical sampling techniques to the problem of damage assessment.

In a "classical" damage assessment calculation, the precise geographic locations of all actual weapon bursts are specified as inputs, a specific wind pattern over the target nation is specified as an input, and the damage to each of a large number of resource points (typically tens of thousands) is computed and summed to produce national totals. A major disadvantage of this approach is the large amount of computer time required for a single calculation. An even greater disadvantage is the fact that the computation is done for only one set of wind conditions and only one precise set of weapon burst points. In actual fact, population fatalities are very sensitive to the wind pattern because of fallout effects. Damage is also sensitive to chance variations in which of the weapons actually impact and exactly where they impact, because of delivery accuracy, abort and penetration probabilities. Thus, in order to assure representative results from a "classical" damage calculation, it must be run a number of times with representative sets of weather patterns and representative sets of weapon impact points. This requirement further increases computing time by a large factor. In contrast to the "classical" method, the system proposed here makes use of statistical sampling techniques, both to reduce the required computational effort and to permit more precise and reliable calculations of the weapons effects.

The basic computational principle of the system can be described rather simply as follows. Let us suppose that we are interested in

calculating the fraction of U.S. population which will be killed by an attack which is specified in terms of desired ground zeros (DGZ's). Thus we are given a list of the latitudes and longitudes where the weapons are aimed, the probabilities that the weapons will actually arrive, and their accuracies, yields, heights of burst, etc. Let us further suppose that we have available a large number of representative weather maps of the U.S., either historical weather data for a long period of history, or else a model which will generate such weather maps and faithfully preserve the known statistical facts, including time and space correlations, concerning U.S. weather.

Now we perform the following hypothetical experiment. First we select one of the weather maps at random from the representative set. Next we convert the desired ground zeros of the given attack to actual burst locations (AGZ's) according to the specified probabilities, by using a table of random numbers. Finally we select a single individual from the entire U.S. population completely at random (so that every individual in the country has an equal opportunity of being chosen). The chosen individual then has a precise geographic location. Given this location, together with the weapon impact points, weapon yields, and national wind data, the weapons effects in his immediate environment may be computed. This weapons-effects data, coupled with sheltering information may be used to calculate the probability of the individual's survival (or other casualty data).

Now what we are really interested in is the expected, or average, fraction of the U.S. population which will be killed by this attack (taking into account the variations in wind conditions and in actual weapon delivery). An interesting mathematical fact, however, which we can capitalize on, is that this expected fraction of the nation's population which will be destroyed is precisely equivalent to the probability that a single individual selected at random from the total population will himself be killed. The hypothetical experiment just outlined did

indeed select an individual at random (together with random weather and attack conditions) and then computed the probability that he would be killed. If this experiment is repeated a large number of times the average value of this sample kill probability will approach the true expected fraction of population destroyed by the given attack.

The method of calculating involves a Monte Carlo process which is applied not only to the wind pattern and actual weapon-burst locations but also to the statistical selection of an individual from the total population. Like many other Monte Carlo calculations the method achieves computational efficiency by combining a number of random processes into a single calculation (the selection of wind conditions, the selection of actual weapon bursts and the selection of the individual). The more conventional method requires separate computation and addition of all combinations of these quantities with consequent spectacular increase in computation time.

Because the approach permits the use of a detailed damage assessment for each sample point, it is possible to obtain a wide variety of detailed information on the damage produced. For example, in addition to requests for the expected fatalities or casualties in the population, one could ask for the average radiation exposure received by the population, the average thermal pulse received by the population, the average of the logarithm of the $H + 1$ dose rate received by the population, etc.

One could also make requests for information such as the expected blast fatalities among urban population, the expected fallout fatalities among the population in the suburban fringes of the 25 largest cities, the average dose received by blast survivors in the most urban 25 per cent of the population, the expected thermal loading in calories per square centimeter among the population of the northeast heartland.

The use of detailed analysis of the individual sample also makes it possible for the system to provide the joint multivariate distribution.

For example, one could request a table of the joint distribution of biological dose versus blast overpressure received in the total population. Among many other possible examples might be the distribution of H + 1 hour dose rate among the population surviving blast effects, or a distribution of the time of fallout arrival versus H + 1 hour dose rate versus biological dose among the urban population, or blast overpressure versus initial neutron and gamma flux, or thermal load versus blast overpressure. Just as in the case of simple averages, these distributions may be specified over any subset of the population.

Because of the use of sampling techniques one can obtain an analysis of variance which will estimate the variability of any function of the sample data with respect to weather variations, attack variations, or the uncertainty in planning factors. A very pertinent question often is: How much variability in total U.S. casualties can be expected because of the chance effects of wind patterns? The total fatalities which would occur on one day with one particular wind pattern are often quite different from the fatalities which would occur on a different day with another wind pattern. It is often quite important to be able to estimate the degree of this variability. Note that here we are speaking of a true (physical) variability, not just statistical variations brought about by our population sampling procedures.

To provide as useful a tool as possible the system will include the ability to perform comparisons of matched sample sets. Often one is interested in the question of small differences which might be brought about by small changes in attack specifications or in civil defense posture specifications. If these differences are sufficiently small they might be masked by the sampling error of the calculation process. However, by performing the calculation on matched samples, whereby the same population samples are used for each calculation, the same wind pattern, and the same weapon burst sets, one can directly compute the difference in effects on each sample point before doing the statistical summarization.

This method of handling matched samples allows even small differences to be computed with high precision. This approach would be recommended for such problems as estimating the change in population casualties due only to a small shift in the intended geographic attack pattern or small changes in the population sheltering posture.

Since the basic efficiency of the system derives from the sampling process (rather than from compromises and rigidities in the basic weapons-effects models in order to achieve low running times) such a system can be extremely flexible and easy to adapt to changing requirements. For example, alternate fallout models can be included and directly compared in a very comprehensive fashion.

In a typical run of the system a large representative set of wind patterns and weapon-impact sets will have been sampled for reliability of results. It is important to realize that the precision attainable by this system is not any less because of its use of sampling than other systems which do not sample. A "classical" damage assessment program would have to be run many times and post-computing analysis made to achieve comparable precision because of the variation in results due to wind and attack variability. The error variance due to the population sampling is generally not the limiting factor in attaining precision.

The basic statistical methodology required for a system of this type was originally developed about fifteen years ago and was incorporated into an analysis system called BRISK/FRISK. We have reviewed this system and believe it can provide a basic statistical foundation on which a modernized system can be most economically developed.

The next section describes the old BRISK/FRISK system which embodied many of these basic concepts.

2.1.1 Background

BRISK/FRISK. BRISK/FRISK is the original (and perhaps only) statistical sampling approach to national damage assessment. The first version of the system in the early 1960's treated only blast and fallout effects, allowed only two population subdivisions (urban & rural), and was restricted in its allowed population shelter posture (either the same shelter over the whole nation or a few simple variations by gross geographic regions or by discs around principal cities). A more sophisticated version developed in 1966, called BRISK/FRISK II, was considerably more comprehensive and flexible. For example, each sample point could carry along any variables available on census tract tapes, READY, TDI, or other primary sources. These variables may be used as inputs to the sheltering model in any way the user chooses. Weapons effects in BRISK/FRISK II included not only static over-pressure and fallout, but also:

- Dynamic pressure
- Pulse duration for static and dynamic pressures
- H + 1 dose rate
- Integrated biological dose
- Integrated dose unattenuated by biological recovery
- Initial neutron flux
- Initial gamma flux
- Total effective direct radiation
- Unattenuated thermal pulse data
- Fallout and blast arrival times.

Most of the above data was available for both the first and second most significant weapons. Radioactive fallout contamination, however, was accumulated over all weapons contributing to the dose at each sample

point. BRISK/FRISK II permitted analyses of damage effects in any subsets of the total or surviving population, definable by functions of the data associated with the sample point--both original data descriptive of the sample and weapons-effects data provided in the computation. The division into two major programs (BRISK and FRISK) was motivated by efficiency considerations. The BRISK program computed the nuclear weapons effects environment about each sample point and added this data to the demographic data descriptive of each sample point. FRISK then processed BRISK output and in a single run evaluated the damage for a number of population shelter postures as well as computing all statistical summary outputs. This division of effort seems worth retaining in the design of a new system. BRISK/FRISK II has not been used since 1972. However, tapes and listings can be obtained to reconstitute the old capability and provide a framework for development of a new damage assessment capability to fulfill the needs discussed in the next section.

Current Damage Assessment Requirements. There appear to exist new requirements in the damage assessment arena that no current operational system can meet. Some of the basic requirements for dealing with the variation and uncertainty in the damage assessment estimates could be accomplished without making any substantial changes in the old BRISK/FRISK system. For example, great interest exists today in addressing not only expected values based on more or less deterministic input, but also the uncertainties in calculations of fatalities--uncertainties due both to the difficulty of assessing potential Soviet threats to the U.S. and to problems in testing the adequacy of U.S. war plans. In addition, most damage assessment systems--COBRA, TANDEM, SIDAC, READY, etc.--are very time consuming and expensive to run. It would be desirable to have a potentially fast running capability. Both of these capabilities (evaluation of variability due to uncertainty and fast running potential) can be provided for DNA with a new damage assessment system built on the old BRISK/FRISK capability.

The recent controversy concerning uncertainties in the estimates of U.S. civilian casualties that might result from Soviet limited nuclear strikes against U.S. ICBM installations underscores the need for a quantitative capability for addressing such uncertainties. The uncertainties that need to be addressed include: uncertainties in the basic weapons-effects models, uncertainties in the nature of an attack, uncertainties in the meteorological conditions which will affect the fallout deposition patterns, and uncertainties in the civil defense posture of the population--such as the degree of evacuation that may be achieved and the extent of shelter from blast and fallout that might actually be utilized. Some of these uncertainties such as those due to wind variation and uncertainty about AGZ's (Actual Ground Zeros), could be addressed directly by the old BRISK/FRISK system. Models of several other variables about which there is uncertainty could also be constructed, but it would require substantial modification and redesign of the existing system to provide a convenient user-oriented analysis capability. Among these would be included uncertainties about the actual reliability, penetration probability, and accuracy of weapon systems and uncertainties about weapons effects.

The statistical assessment system based on random sampling described in this report can provide not only the desired explicit approach to uncertainty analysis but can also be used in a relatively quick response mode to provide estimates of known precision for overall national damage levels. Evaluation of damage to only a relatively limited collection of sample points provides an estimate of the national damage in very little run time. High precision expected value, variance and distribution information can be obtained after exploratory analysis in the fast-running limited-sampling mode.

In the evaluation of U.S. war plans, there is a need to produce not only single estimates of damage, but also confidence bounds on such estimates. Probably the best way to provide such confidence information is by giving the user an estimate of the full statistical distribution. The

implication of a need for fuller distribution information exists in general in the community. Although old BRISK/FRISK did not include the capability to develop such distributions, our theoretical analysis indicates that the new system can be designed to derive efficiently not only expected values and variances but also representations of the entire distribution.

The analysis of strategic planning uncertainty should also go beyond environmental and modeling uncertainties to include uncertainty in the planning factors used to generate the war plan. These inherent uncertainties are an important and high order determinant of the success of strategic planning. The development of plans that can successfully hedge against such uncertainties is one of the most difficult aspects of strategic planning. The annex to this report provides a broad review of the extent and seriousness of some of these problems. Although the war planners (particularly for the SIOP) go to great lengths to hedge against such uncertainties, the verification that the plan is adequate often takes the form of running only a few off-design cases. Thus there is a clear need for a damage assessment system designed to validate the hedging strategies used in the development of such war plans. As we will describe, statistical sampling of planning factors, prior to the sampling of specific AGZ's, winds, etc., is an efficient device to determine quantitative performance of war plans under conditions of uncertainty.

A final requirement that the new system is inherently suited to satisfy is that of serving as a standard of calibration device for other systems or component models. In that role the new system will show the range or distribution of outcomes, so that results obtained with other damage assessment systems or different weapons-effects models can be positioned in that range. One can then determine whether a damage assessment system used with specific winds and attacks produces results within an appropriate statistical range of the standard (one standard deviation, perhaps) or consistently falls to the high or low side of the mean of the distribution. In that a proliferation of systems will probably always

exist, despite efforts to standardize, it is useful to have a system against which other systems can be tested and calibrated.

2.1.2 Categories of Uncertainty

In order to design a comprehensive system to deal with the variability and uncertainty in damage assessment calculations it is necessary to provide an orderly classification of the sources of uncertainty that enter into the calculations. The following sections provide a review of these uncertainties in the order that they are visually encountered in a damage assessment calculation.

Uncertainties about War Plans, Objectives. These are the broadest and most important uncertainties in strategic planning. In terms of damage assessment, in the strictest sense, they might not seem an appropriate topic of discussion. But when we reflect on the main purpose of a damage assessment capability--to gauge whether we have an assured destruction capability in designing our SIOP and to estimate the threat to our population, industry, and military systems, from a Soviet attack--it is clear that in any broad assessment of uncertainty we must address questions like who goes first, and what are the weapons, inventories, and targeting objectives? In order to assess damage in the U.S., for example, we need the detailed allocations of Soviet weapons to targets and specific DGZ's. These are ultimately subject to uncertainty, some of which derives from our own orientation to precede any countervalue attacks with counterforce exchanges.

However, the exploration of the effects of different war plans on damage outcomes really requires a capability to generate such a range of war plans to be tested. This clearly goes beyond the scope of capabilities that it is reasonable to incorporate in a damage assessment system. The development of war plans is a major undertaking that clearly must be accomplished outside the damage assessment system. The second section of this report gives a rather full description of the problems

in war plan generation under conditions of strategic uncertainty. For our present purposes, the system will be designed primarily to evaluate the uncertainties that remain after a particular war plan has been selected.

It may, however, be possible to include a capability to sample from a selection of predefined war plans. If, for example, the uncertainty corresponded to an enemy decision for counterforce or counter value targeting, evaluation of either such extreme war plan separately would allow any probabilistic mixing of outcomes, if the user specified the likelihood of such occurrences. (Internal mixing of diverse war plans, say by adjusting the probability of arrival figures for all the DGZ's to reflect the likelihood that one or another plan is selected, cannot be used because it leads to erroneous results. Only one plan can be executed, so the probabilities of arrival are not independent but completely correlated.) Consequently to deal with this type of uncertainty the attack sampling must be generalized to parallel the wind sampling, so that a probability mix of diverse war plans and objectives can be evaluated.

Uncertainties About Planning Factors. This next category of uncertainty has been discussed briefly in the earlier parts of the report. We consider it an essential element of a complete damage assessment capability to reflect the range of outcomes induced by uncertainty in planning factors, namely all the input parameters that go into evaluating the outcome of a war plan. Among the key factors are

- Probability of destruction before launch (DBL)
- Reliability
- Penetration probability
- Delivery accuracy
- Warhead reliability
- Yield
- Fission yield
- Height-of-burst
- Time-of-arrival

Normally in the conventional evaluation of war plans these planning factors are treated as if they were precisely known. In fact in many cases they are not known with much accuracy, and the uncertainty with regard to these factors can be one of the most important contributions to the uncertainty in the damage assessment outcome.

To provide a proper treatment of these uncertainties, the system will be designed so that it can sample from a probability distribution of these factors. A single random draw will produce a specific value for each of these planning factors. After the planning factors for a set of trial samples have been selected, the individual weapon delivery and AGZ's can be developed by the usual Monte Carlo methods. In this way the uncertainty in planning factors can be directly assessed in the calculation.

It is worth noting that in order to produce correct results it is necessary to take into account the correlations in planning factor errors. For example, if the reliability of Polaris has been under-estimated, it is extremely likely that the reliability of Poseidon has also been underestimated. If the penetration probability of cruise missiles has been overestimated then it is very likely that the penetration probability of bombers has also been overestimated. Consequently the total uncertainty is likely to be substantially higher than one would expect if all such estimation errors were uncorrelated. The system will be designed to make it as easy as possible for the user to take such correlations into account if he wishes to do so. It will also be designed so that he can ignore the correlations, and indeed can ignore all uncertainty in planning factors when he wishes to do so.

Uncertainties in AGZ's. This category of uncertainty is concerned with the uncertainty about which specific weapons are actually delivered successfully and about the actual impact point for the weapons, assuming

that both the war plan (the desired ground zeros) and the associated planning factors are known. The capability to deal with these sources of uncertainty was included in the original BRISK/FRISK system. The Monte Carlo methods for simulating these uncertainties are known and do not require any comment here. Experience in the early application of BRISK/FRISK, however, showed that these factors do not usually produce any large uncertainty in nationwide damage levels, although the uncertainty in damage to individual targets can be very large.

Uncertainties About Target Environment and Target Characteristics.

Among this group are the following important factors which are too often treated in a deterministic way:

- Target hardness or vulnerability
- Fallout winds, cloud cover, rain, snow cover
- Shielding factors for population
- Population location, especially for evacuating or evacuated populations.

The new system will be designed so that it can address all of these factors to the extent that suitable models are available. At present satisfactory models are available for all of the above factors except population evacuation and the relatively minor issues of cloud cover, rain, and snow cover. The system will be designed in the modular way so that it can accept any population distribution before or after relocation. This will make it easy to interface the system to any population relocation model. It will also be designed to accept as conveniently as possible models that represent the effects of cloud cover, rain, and snow cover, when such models become available.

Uncertainties About Weapons Effects Models. Varying degrees of uncertainty accompany all weapons effects, including:

- Blast
- Initial nuclear radiation
- Thermal
- Fire, firestorm
- Fallout

In the new system different effects models can be compared and, in fact, random sampling could be used to reflect uncertainty in the parameters of weapons-effects models.

Uncertainties About Interactions Between Weapons Effects. The information for interaction analysis will be available in the system. A model for the effect of one damage mechanism or another must, of course, be supplied. The specification of the nuclear environment will be as complete as possible when interactions are examined, and uncertainty here could be modeled through random sampling as described above.

2.1.3 Outline of Proposed System

Basic Logic. The approach, as we have discussed, is based on statistical sampling. Hence, the idea of drawing samples (of attacks, winds, population) is fundamental to the description. A typical calculation might proceed as follows. Prior to the run a file is prepared with many sets of population samples, each sample corresponding to 20 to 30 individuals randomly selected from the population. It is important in arriving at the expected damage that each individual in the population have an equal probability of being included in the sample. The highest resolution data bases can be the source of the samples or they can be drawn from more aggregated data bases. Two basic processors are defined so that the more lengthy weapons effects calculation need not be repeated in order to process a series of population postures in a single run. The second processor handles population response and all statistical calculations and

and summaries. In the first processor, a set of planning factors are drawn first from distributions which preserve any correlations in probability of destruction before launch and reliability (including yield, height of burst, etc., among the attack descriptors which may be subject to uncertainty). Input information to this processor describes the attack in terms of DGZ's and weapon characteristics with further descriptors of the uncertainty distributions about these values, as well as any correlations between the variables. The randomly selected set of planning factors then serves to define an attack in terms of weapon descriptors and probability of arrival for each weapon. This is used in the later selection of AGZ's in the normal mode of operation. When planning factors are not subject to uncertainty this stage is bypassed and the attack plan is an input (DGZ's, CEP, yield, height-of-burst, probability of arrival, etc.). Thus, the basic modular calculation first draws a wind map, an actual attack, and a population sample, and proceeds to determine the nuclear environment about each individual in the sample. This process in the normal mode is repeated perhaps 50 to 100 times.

The weapons effects routines can be completely modular and should include all effects that are relatively well enough understood to represent as a form of effect versus distance relation. The purpose here is to add to the normal population sample descriptions the descriptions of the nuclear environment (overpressure, dose, etc.).

The second processor is charged with translating the nuclear environmental information into actual probability of fatality and casualty for specific descriptions of the population response function (sheltered, evacuated, etc.). The first phase determines the weapons effects and the second phase the population response. This separation allows the evaluation of many shelter postures within a single run.

We specified the "normal mode" above because several other modes can be defined. In particular, consider wind variance and attack variance

modes. Visualize three urns containing winds, attacks, and sample points. In the normal or expected value mode, one draws samples from all three urns before undertaking each new calculation. In the wind variance mode, it is more efficient to sequence through several winds while holding the sample point set and the attack constant. In the three urn analogy one draws a wind, attack, and a sample point set, and performs the first variable calculation. For the next several calculations only a new wind is drawn, leaving the sample set and attack fixed. Finally, once a sequence of several winds has been drawn and treated, a new attack and sample set is drawn, and a new sequence of winds is drawn. This process is repeated until several attack/sample set samples and many wind samples have been examined.

In the attack variance mode, several attack samples are drawn for each wind/sample set sample. This mode is just like the second mode except that the roles of winds and attacks are interchanged. The design for the new system should, of course, retain these basic capabilities. However, to provide a broader analysis capability the user will be permitted to select any combination of the uncertainties to be evaluated in a specific analysis. The system will then provide statistical results--mean and variance as well as an assessment of the probability distribution if it is desired.

The sequence in selecting population attack and wind system samples constitutes an opportunity to use experimental design methods with even firmer control than a real world experimenter could wish for (owing to the possibility of cycling over the same set random variables for comparisons, which eliminates error variance). By using a sufficiently large number of samples, any desired degree of accuracy can be attained. Furthermore, the variance due to the variability of attack and wind samples can be reliably ascertained by normal statistical methods.

When the complete sample (constituting the sample point set, the actual attack, and a national wind map) has been assembled in any one of the modes, the nuclear environment can be determined for a multitude of weapons effects, limited only by the necessity of a representation for later translation into casualty or fatality information in the second processor.

Executive Control. To supply full user control and a simple transparent mode of operating the new system, a special executive control will be provided. Thus, the sophisticated programmer can call upon the full flexibility built into the system, while the more typical user will not necessarily be aware of any features beyond those he demands for the problem at hand. A capability for "what if" questions seems desirable as well. For example, the user may desire to vary (subject to random selection) only preselected elements of evaluation. Thus, planning factors may be certain, but AGZ's, winds, and shelter postures may be subject to uncertainty. Simple, knob-like control of the variance analysis can be provided.

Expected Values. The unusual mode of sampling in each modular calculation estimates damage to a set of population points (a population sample). Each such point represents a randomly selected individual from the population and the damage calculated is therefore an estimate of the expected damage to the whole population. Thus, the averages of very many such modular calculations is a highly accurate measure of the true expected damage, and standard statistical techniques indicate the degree of precision of the estimate as well. Thus, one might run a small set of samples to gain a quick estimate of the national damage with known precision and use more extended runs to investigate special details, determine variances or derive full distributions.

Variances. The analysis of variance capability in the system can be used not only to isolate attack and wind components of variance, but

also the variance due to uncertainty in the planning factors. Often this source of uncertainty may be simple lumped with the attack variance, since the nationwide variability due solely to sampling probability of arrival (converting DGZ's to AGZ's) is generally quite low. Experience with the older system indicates that wind, rather than attack, variability is the dominant parameter. With planning factor sampling in the new system, the variability due to uncertainty in the attack will be magnified. Of course, if uncertainty in war plans or objectives is represented specifically in the new system, then the effect on the attack variability will be further heightened.

Distributions. An innovative technique has been devised based on Bayesian inference to represent in the new system the full distribution of outcomes. This is critical from the viewpoint of verifying attack plans, since the mean and variance are not a full enough description for the high confidence criterion planners often desire. Ninety percent confidence bounds will be derivable in the new system, for example, with full distribution information available when such detailed statistical information is deemed of importance. For analysis of opposing "limited" nuclear strikes on the U.S. or Europe, a determination of the bounds on the range of possible outcomes is often of more importance than evaluation of expected damage.

Planning Factors. Explicit sampling of planning factors is a recommended feature for the new system. As discussed in the Appendix on strategic uncertainty, it is uncertainty in planning factors that motivates much of the distinctive character of U.S. war plans (and even strategic force procurement from a broad point of view). The ways weapons are targeted (cross targeting, for example) are intended to hedge or lead toward a guarantee of certain required levels of damage even when systems fail to perform as planned, or enemy systems work better than anticipated. The new damage assessment capability will for the first time allow a planner to explicitly reflect these uncertainties in the assessment itself and from the range of outcomes and the statistics of

occurrence of undesirable outcomes, verify that the plan indeed leads to accomplishment of national objectives.

Data Bases. Because the population sampling function precedes the first processor, no limitations on data base accessibility are foreseen. The finest grained representations available can be sampled, given only that the individuals chosen all have identical probability of selection. Because the system looks at the sample points as individual members of the "population" under investigation, even a data base containing 250,000,000 items, one describing each person in the U.S., could easily be handled. TDI, READY, TANDEM, or other data bases with which we are familiar seem to present no special problems, with the obvious exception of insufficient or incomplete data about the population under study (e.g., rural population missing from the data base).

Point Representations. Because the samples are composed of point representations of the population--latitude, longitude, description of shelter and surroundings, etc.--grid or cell representations which lead to smoothed area approximations in calculation of effects are avoided. This is a significant advantage over every damage assessment system with which we are familiar. In the new system, there really is no limit on the fidelity with which the physical effect of a weapon burst at a specific latitude, longitude, height of burst and time of burst can be represented on an individual at a specific latitude, longitude and shelter environment. Because we depend on sampling rather than exhaustive examination of the whole population (or cells, smoothed groups of population, as usually dictated by reasonable run time requirements), efficiency doesn't imply approximations in weapons effects representations.

Matched Samples. To determine the variability due to small changes in the assumptions, the matched sample technique is invaluable. The same set of population samples winds and attacks with different input isolates the effect of the change and overcomes the problem of imperfect resolution

due to the sampling itself. That is, without matched sampling, the sampling error might tend to obscure the effect of the change. In the matched sampling mode, the statistics are taken over the difference in results for the two cases. An original application of the old BRISK/FRISK system was to determine the effect of a Soviet attack on U.S. targets where the variable quantity was the original MM site locations. Because the locations under consideration were all rather isolated, different siting choices did not lead to easily observable changes in U.S. national damage. Yet with matched sampling the differences could indeed be seen even though DGZ's were only perturbed by slight variations in the locations of MM sites.

Comparison of Weapons-Effects Models. For DNA, capability to examine the effects of different assumptions or models describing weapons effects, (fallout, for example) seems very useful. Again, a matched sampling technique can highlight even small differences induced by different model assumptions. Models of the interaction of weapon effects, often simply assumed independent, can also be accommodated in the system, since the actual damage is evaluated only after the full description of the nuclear environment has been attached to each sample point. Here, too, to distinguish the results of any specific synergy that might be postulated, matched sampling is essential.

Weapons-Effects Models. No limit is put upon the weapons effects that can be included. The old BRISK/FRISK simply included curve fits to the standard weapons effects from Glasstone. Current codes describing effects versus distance, time of arrival, etc. can all be accommodated. The latest representations will be incorporated and multiple representations will be included when comparisons can be foreseen as a research task. Even the old BRISK/FRISK included two fallout models with provision for more, if desired.

Sample Level Diagnosis of Results. For the new system, a capability for comparison and diagnosis not only of changes in national totals, but also of changes in the effect at the individual sample level will be provided. Thus one can identify the cause of different results from different fallout models, say, by observing that one model treats a sample in a certain overpressure region quite differently than another fallout model. One model may tend to "waste" fallout in higher overpressure regions or high thermal pulse regions. Since the environmental data is attached to the samples, this new capability amounts only to an expanded reporting or summarizing capability.

Weighted Sampling. By allowing samples to be weighted, one can convert the data obtained by sampling from one population data base to final statistics valid for different census years or for population, movements across census tract boundaries to shelters or to evacuation sites. The use of weighted sampling should also permit more efficient calculation of results for resource categories such as steel that are dominated by a few installations which should be exhaustively sampled.

Subsets Statistics. Estimates can be supplied for selected subsets of the original population where the definition of the subset can involve any of the data attached to the sample. Thus, urban blast fatalities can be presented, or average fallout doses among blast survivors in the suburbs could be derived.

Joint Multivariate Distributions. A table of joint distribution information can be provided. The system simply uses each calculation to increment counters in computer memory for various ranges of outcomes. These counts are converted into joint distribution formats in the summaries. Thus, one can obtain the distribution of biological dose among blast survivors or thermal load versus blast overpressure. Again, any of the data items associated with the sample points can key the distribution. Also, any subset of the population can be specified for a joint distribution summary.

2.2 BASIC PROCESSING LOGIC

We next discuss some details of the logic in the two main processors of the new system. The first processor is concerned with the determination of a variety of weapons effects in order to characterize as fully as possible the nuclear environment about each sample point. The second processor evaluates damage for a variety of population protection postures and computes all statistical summaries. These processors correspond to the BRISK and FRISK programs of the old system. We next discuss the preparation of the population sample tape. In this regard, the term population, while generally denoting people, can be generalized in the sense of any "statistical population" contained in a data base--industrial facilities, livestock, radio stations, etc. The logical flow in the system is depicted in Figure 1.

2.3 1ST PROCESSOR: WEAPONS EFFECTS COMPUTATION

2.3.1 Introduction

The role of this element of the new system is to read the population sample tape previously prepared, and to add to sample point data new information describing the nuclear environment produced by the attack. In most general application a modular calculation consists of first drawing a set of planning factors, which will in general not be the same as those for which the attack was generated. This will apply only to evaluation of U.S. plans in most cases. Then AGZ's are drawn, given the planning factors and the DGZ's. A weather (wind) pattern (nationwide) is drawn and the various modular routines for nuclear weapons effects are then called one by one. None of the original weapons effects routines developed for BRISK/FRISK will likely be retained in the new system. The latest codes for the pertinent physical effects of nuclear weapons will be applied.

2.3.2 Input

Population Sample File. The foundation of the system is the use of random population samples for estimation of national damage. Consider

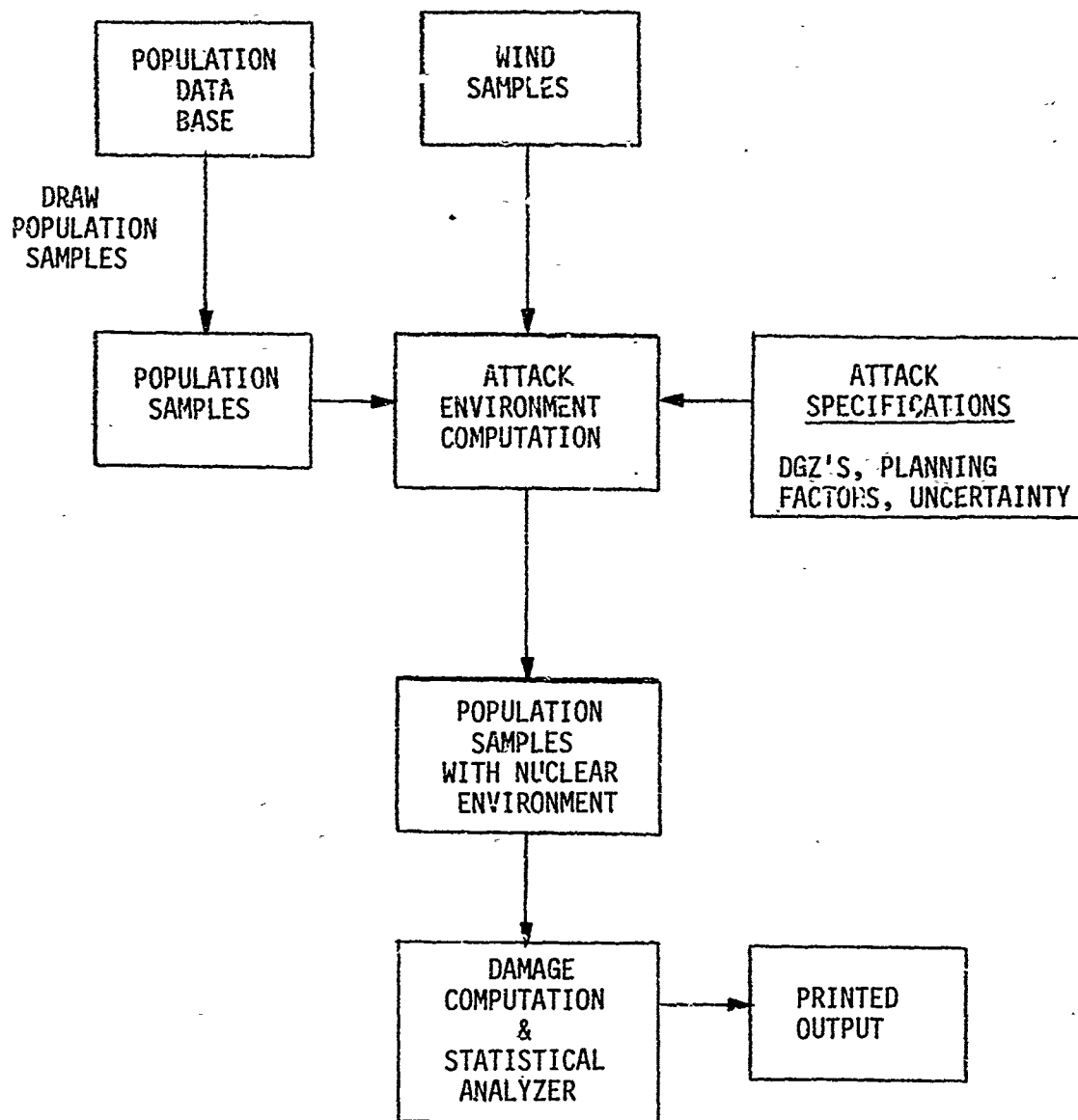


Figure 1. Flow Diagram

a data base such as census tract tapes. In any tract, all people are essentially identical. The problem is preparing a tape of samples such that all members of the population have an equal chance of appearing. If some 8000 samples are to be drawn, this determines the probability that an individual will appear. As each tract is processed, there may be no individual selected, or one, or perhaps more (the record is simply repeated as another sample). Once a set of samples are taken in this sequential manner, the records are shuffled by standard means, producing a randomly ordered set of records, each describing a sample point, or individual member of the population.

Other population (livestock, agriculture, etc.) may also be processed. If only a few thousand such items exist in the data base, the entire population may be processed.

Attack Plan File. Unlike the population sample and wind file, only the description of the attack plan is contained in this input. A generalization to consider a probability mix of possible attack plan (uncertain objectives of the attacker) would imply a series of nationwide DGZ patterns and descriptive data, similar to the wind file, which has perhaps several hundred nationwide wind patterns. The normal operational mode, however, draws random attack samples from the DGZ and probability of arrival data in the attack plan. When planning factor uncertainty is specified, a preliminary draw of these factors precedes the conversion of DGZ's into AGZ's. Data on the attack plan file then must include a description of the uncertainty distribution about each planning factor.

Wind Sample File. The wind file contains a series of sample wind maps. Each wind map consists of wind data specified on a rectangular grid of points (of optional grain size) laid over the geographic region of interest. These wind map samples can be based on historical data, or can be generated synthetically through a technique developed

by Dr. George E. Pugh, which was adapted for the old BRISK/FRISK system. The artificial wind maps preserve space and time correlations in the winds and produce weather patterns that appear plausible to professional meteorologists.

2.3.3 Calculation of the Attack Environment

Given a population sample, a wind map and a set of AGZ's and weapon characteristics, it is straightforward to calculate the weapon effects through standard effect versus distance functions, which could be represented by curve fits to data and charts in the nuclear weapons effects manuals (as was done for BRISK/FRISK) or simply by fine-grained table look-up procedures. Essentially a new menu of such codes should be considered for the new system to reflect improvements in representations and knowledge of effects over the recent years.

The output of this phase is a set of person-by-person records containing both the original sample variables from the input sample tape and a set of additional variables describing the attack environment.

2.4 2ND PROCESSOR: POPULATION RESPONSE & STATISTICAL COMPUTATION

2.4.1 Population Response

The first main task of this processor is to convert the nuclear environment data into actual casualty or fatality estimates. The input consists of a sequence of sample points, to each of which is attached population data, shelter data, and attack environment data. The population response subroutines can be completely modular. The idea is to add still more descriptive variables to the sample point records, prior to the final phase of statistical processing. Several different shelter postures can all be evaluated at once. By weighted sampling, different populations, say 1980 and 1985 U.S. populations, can be evaluated in a single run.

2.4.2 Statistical Processing

The following capabilities exist in the old BRISK/FRISK system and should be transferred to the new. One can obtain:

- Mean values
- Wind variance
- Attack variance
- Joint multivariate distributions.

In addition, techniques appear feasible to formulate not only mean and variance information in the basic statistics, but full distributions which will allow confidence level, or percentile, outputs to be generated. A note on the variance technique in BRISK/FRISK may be useful. As mentioned before, attack and population samples are held fixed while winds are varied in the wind variance mode of operation. This, of course, gives the variability for the specific fixed attack. For another attack, presumably the variance would be different. Thus, a series of attack/population samples are drawn. For each, many random wind samples are examined. The average of these wind variance measurements for many attacks is then the output estimate of the wind variance. A similar method leads to the estimate of attack variance.

2.5 DATA BASE CONSIDERATIONS

Any data base, aggregated or fine-grained to an extreme, is accessible for extraction of a set of random samples from the data base. In the case of tract, cell or even more highly aggregated groupings, there may be repetitions of the same data set since so many individuals in the population are grouped together with identical descriptions at the same latitude and longitude. Conversion from data base format to that for the damage assessment processing is usually a routine job.

Note that the sample function is separate from the damage assessment procedures. Different samplers can be prepared for different data base applications in a routine manner.

2.6 RECOMMENDATIONS

We recommend that DNA proceed to develop the new damage assessment capability as outlined herein. The tactic of first securing the old BRISK/FRISK programs, making key elements operational with test data, and then successively adding new modules, modifications and refinements to produce the new system seems most promising. Such a gradual, evolutionary development trajectory virtually guarantees successful completion, if each step proceeds satisfactorily. Economically, a savings in recreating statistical codes is obvious. It appears to us that an operational capability with realistic data might be achieved from commencement of development.

APPENDIX A

STRATEGIC UNCERTAINTY

A.1 INTRODUCTION

As described in the main section, the eventual goal of the current project is to systematically characterize the variability in outcome of a nuclear attack. Almost all damage assessment systems present deterministic or expected results, while all real attacks are subject to many uncertainties that inevitably lead to a dispersion of results. We believe that a representation of the distribution of outcomes can be obtained as a function of various uncertain factors by a process of statistical sampling, which can lead to a very full description of damage variability. Furthermore, a higher resolution expected-damage calculation can be accomplished in significantly reduced computer time compared with current damage assessment capabilities by the sampling approach.

It seems useful to supplement our more detailed design concepts by a general discussion of strategic uncertainty. In this context, it will be clear the extent to which the new system has been designed to illuminate uncertainties and implied variability in outcome due to:

- Uncertainty in the attacker's objectives (if we are interested in assessing damage to our own target system)
- Uncertainty in the attack planning factors (for evaluating our own war plans)
- Uncertainty in the actual attack (AGZ's, yields, HUB's)
- Uncertainty in the target system (hardness, population sheltering, population location under evacuation, etc.)
- Environmental uncertainties (fallout wind patterns, cloud cover, etc.)

In this portion of our discussion, we shall mention various types of uncertainties, ways of classifying them, methods of treating them to predict their effects, techniques of attack planning to hedge against them, and their impact on damage assessment systems that would measure the range of results induced by such uncertainties. Both inherent uncertainties, such as those produced by the unpredictability of fall-out winds (in any detail) and potentially unanticipated uncertainties in planning factors can be reflected in the new damage assessment system.

These considerations tend to impact not only the principal area of our concern, damage assessment, but also the area of attack planning. Since a good war plan implies one developed to cope with uncertainties, a good damage assessment system should reflect the variability of outcomes contingent upon the same uncertainties. Thus, war plan generation systems and attack evaluation systems should be quite complementary to each other. At present, however, the goals and objectives of either capability are set quite independently.

In the sections that follow, particularly the description of attack techniques to hedge against uncertainties, this complementary viewpoint is emphasized. Whether in evaluation of a U.S.S.R. threat or in verification of the adequacy of a U.S. war plan, present damage assessment capabilities are inadequate in their consideration of uncertainty. We hope this discussion will illuminate how important it is to develop a consistent consideration of uncertainty over the spectrum from plan generation to attack evaluation.

A.2 DIFFERENT WAYS OF CLASSIFYING UNCERTAINTIES

A.2.1 Introduction

In order to be reasonably comprehensive in discussing the various uncertainties to which strategic forces are subject and

therefore to which strategic attack planning and attack assessment should be sensitive and responsive, we outline and discuss here a number of categories of force interactions and uncertainty types.

A.2.2 Many-On-Many VS. One-On-One Interactions

Different and new elements of strategic uncertainty enter when large force exchanges are to be examined instead of isolated weapon-target interactions. On the smaller scale, all sorts of properties such as weapon yield, accuracy, height of burst, target hardness, location, etc., are subject to uncertainty. The treatment of uncertainty may take the form of questioning whether the damage function adequately reflects the expected result, expanding the representation to produce confidence bounds, or even including a more explicit form of one or more of the uncertainty distributions in the objective function itself, perhaps integrating over this uncertainty to obtain expected damage. Uncertainties may exist in factors that act jointly; this complicates any treatment. The largest scale force interactions encompass additional uncertainties in deployment, employment, intentions, etc., which need rather different treatment, but benefit as well from the law of large numbers which permits efficient statistical approaches.

A.2.3 Size of Force and Target System

Here we might further categorize uncertainties into local or global categories. In another sense we can distinguish by size from force effectiveness to individual weapon effectiveness as above, and go on to consider multiple weapons on a single target and multiple weapons on a complex target. When several weapons are intended for the same target, particularly the same aim point, questions of shared unreliabilities of uncertain extent lead to cross-targeted allocations. Beyond this, the inherent uncertainties in weapons effects, fuzing errors, etc., raise questions of fratricide in certain situations where target hardness necessitates ground bursts. Apart from the difficulty

in conducting such tests, arms control agreements make it almost certain that the precise effects on warheads of passage into the environment created by another nuclear burst will remain largely unknown. Hence an attack planner must develop strategies to hedge in such situations where the uncertainty is inherent and unremovable. Additionally an attack assessment should reflect the inherent dispersion in potential results.

Multiple weapons on a complex target or a target of uncertain location are best placed in a pattern to optimize results. But if reliability is 50% and ten weapons are being allocated, choice of the ten aim points changes as the uncertainty in the reliability figure is allowed to increase. In past work we have examined how to hedge for uncertain reliability in DGZ selection and included discussion of conservative and optimistic strategies, and strategies to maximize expected damage in complexes of targets. Such strategies will be discussed further on.

Another area of uncertainty associated with target complexes is production of collateral damage. Statistical expectations and confidence bounds are appropriate, of course, but joint consideration of uncertainty about target or non-target hardness and weapons effects radii is often overlooked in aim point selection models. The JAPS (Dual Criteria Aim Point Selection) program, for example, always locates an aim point on a circle drawn as far from the target as prespecified damage requirements allow, and then at a point on that circle as far as possible from the non-target (or targets). Obviously, failing to consider uncertainty in the primary factors of the target damage function risks achievement of the planned target damage, since the aim point is offset the maximum distance from the target allowed using "certain" values for the damage calculations.

A.2.4 Complete Knowledge and Imperfect Information

As indicated earlier, the treatment of uncertainty is fundamental to military planning. What goes beyond the routine expected value and confidence level approaches is the consideration that the physical descriptors and planning factors input to these models are themselves uncertain. Beyond the possibility that reliability, accuracy, and related figures are in error, there are a number of further questions regarding the effects of imperfect information. Among these are uncertainty about the total strength of an attack, or about the characteristics of the attacking objects, or on the part of the offense, about the various characteristics of the opponent's defensive equipment and forces. Approaches to deal with these questions are discussed below.

One area where assumptions of complete knowledge are misleading is evaluation of the impact of command and control capabilities. Misestimates of nominal C^2 capabilities themselves should be added to the usual analysis of degraded performance due to imperfect sensors, opponent's jamming, etc.

A.2.5 Current and Future Uncertainties

An appreciation that current vs. future uncertainties need to be handled differently is needed. In a sense, one could imagine future capabilities represented by a two-stage stochastic process. First, from a broad distribution of likely equipment performance parameters we draw the expected values of future equipment capabilities. But, then, we draw again from a narrower distribution about each of these values to pinpoint a single value of a future physical parameter. Technology may induce correlation into the first group of draws, in that a whole collection of future specifications may be better or worse than expected, jointly.

A.2.6 Deliberate and A Priori Uncertainties

We have described many types of uncertainties. All can be further characterized by the important aspect of whether additional

uncertainty is induced by the purposeful actions of the adversary. Basically, the uncertainties that should be considered come in two varieties. The first, termed a priori uncertainty, is non-deliberate on the part of any protagonist; it might exist simply as a result of imperfect intelligence information on the part of any player. Typical properties of attack and defense that are subject to such a priori uncertainties are:

1. Characteristics of attacking objects
2. Characteristics of targets
3. Characteristics of defense systems
4. Amount of withheld forces
5. Intended attack strength against defended targets
6. Proportion of force that will survive enemy first strike
7. Inventory levels of terminal defenses both locally and nationwide
8. Inventory levels at area defense installations
9. Geographic coverage of area or terminal interceptors
10. Environmental factors such as fallout winds, cloud cover, etc.

The second type of uncertainty arises from deliberate randomization on the part of either opponent to improve the performance of his weapons systems--often the exercise of a mixed strategy in the game theory sense. Analogous to this in many cases is the random element introduced by purposeful deception, so as to intentionally confuse the opposition. Typical characteristics of strategic warfare that might be subject to such uncertainties include:

1. Terminal defense deployment (via mobile interceptors or dummy defense emplacements)
2. Area defense deployment and coverage (via dummy area interceptor emplacements and randomized employment among targets)
3. Time-phasing of attack (use of sequential attacks)
4. Selection and employment of penetration aids
5. Defense firing doctrines
6. Tactics with mobile systems

Deliberate uncertainty always involves the actions of an opponent and therefore is inherent to BMD, ASW, ECM, mobile system deployment and employment strategies. Strategic analyses that fail to take into account the possible adversary countermeasures are obviously suspect.

Some divisions of a priori uncertainty are useful for later discussion. First, we can identify weapon and target related uncertainties. These need to be handled differently in estimating damage probabilities from multiple weapon attacks, for example. Among weapon related uncertainties are weapon-weapon correlations in performance. Models of shared unreliability, from DBL through dud probability, lead to cross-targeting strategies that mix different weapon types aimed at the same target.

Even precisely known weapon and target descriptors do not define a precise outcome of a weapon-target interaction. The engagement is a stochastic event with a distribution of outcomes about the expected value.

For small numbers of weapons or targets, the chance variations in outcome that occur with known performance factors can be important.

Target related uncertainties such as geodetic bias or the equivalent problem of attack of area or extended targets, lead to optimum pattern attacks. When uncertainty in weapon performance is added, however, generous (spread out) patterns tend to be pulled in toward the expected target position or area target center. In other words, elegant DGZ selection models could be rather too sharp a tool when they assume complete knowledge of weapon related parameters.

A.2.7 Weapon-Related and Target-Related Uncertainties.

There are two extreme interpretations of the lethal radius distribution, with all intermediate cases possible, of course. Under one interpretation, the fluctuations in lethal radius are independent from shot to shot, and may be regarded as weapon-related (yield variation, height of burst variation, direction of weapon burst for targets of unsymmetric vulnerability, etc.). The other interpretation is that lethal radius is perfectly correlated (constant) from shot to shot on a given target, and that the fluctuations are target-related and represent vulnerability uncertainties or inhomogeneities in the target class.

In the first case, pure weapon-related lethal radius distribution, the survival probability for n shots is simply the n th power of the single shot survival probability, since all shots are completely independent and the target must survive all shots:

$$\text{SURV}(n) = \text{SSSP}^n = \left[\int_0^{\infty} P_L(r) P_D(r) dr \right]^n \quad (\text{A-1})$$

In the second case, pure target-related lethal radius distribution, the lethal radius remains constant from shot to shot, so that the calculation must first be performed for n weapons with fixed lethal radius, and last integrated over the lethal radius probability distribution. For a fixed lethal radius r the probability that the target survives n weapons is the probability that all weapons miss by r or greater:

$$\text{SURV}(n,r) = \left[P_D(r) \right]^n \quad (\text{A-2})$$

The overall expected survival probability is then given by integrating over the lethal radius distribution:

$$\text{SURV}(n) = \int_0^{\infty} P_L(r) \left[P_D(r) \right]^n dr \quad (\text{A-3})$$

The two results are distinctly different, so that the distinction between weapon-related and target-related lethal radius variation may be quite significant. One cannot, therefore, correctly compute multiple shot kill probabilities without understanding the sources of lethal radius variation.

A.2.8 Two-Sided vs. One-Sided Strategies

Certain uncertainties may be overlooked when the strategic analysis problem is viewed purely from one side's perspective, with no attention to countermeasures or deliberate deception. It is in principle impossible to evaluate the effectiveness of a new system unless the opponent's reaction to introduction of the system is also included. Furthermore, the logical need to evaluate for best use of the system in the face of the opponent's reaction leads to requirements for optimal two-sided strategies in many cases. Indeed,

that game theoretical structure is certainly appropriate for any strategic analysis, but may not be formally utilized in specific cases, depending on what is being analyzed. It should always be kept in mind, however.

A.2.9 Mixed vs. Pure Strategies

Since game theoretic techniques are invoked to resolve many uncertainties in strategic analysis, mixed strategies are often the outcome. It should be recognized that only deliberate uncertainties induce mixed strategies. And even here, if one opponent moves after the other, a pure strategy is best. Finally, even in pure simultaneous move games, involving deliberate uncertainties, a conservative pure strategy may be an appealing choice over a mixed strategy offering a higher expected payoff. Since strategic engagement may occur but once, the statistical safety of repeated plays does not guarantee the integrity of the game expected value. For such games, one can immediately perceive the risk in that the probabilistic mixed strategy includes outcomes less favorable than the expected payoff. Hence, choice of a conservative pure (perhaps MINIMAX or MAXIMIM) strategy can guarantee no worse than the deterministic outcome associated with the opponent's best response to the strategy.

A.2.10 Utility vs. Expected Damage Approaches

We shall discuss utility theory applications to strategic analysis at more length in the next portion, but like two-sided considerations, the fact is that utility functions are an appropriate valuation device in any strategic analysis. Hopefully, in many cases, expected damage, or analogous measures, properly mirror the "decision maker's" utilities. But in strategic force planning, and in force posture evaluation and design, contradictions often arise due to inadequate specification of goals that can be encompassed correctly by a utility approach.

For example, an "optimization" procedure based on a confidence criterion can produce decisions which have some very unreasonable characteristics, such as a preference for alternatives with a substantial probability of achieving a very low damage level. This is because they may also offer the best chance of achieving some (unreasonably) high required damage level. In effect, the "confidence" criterion "optimization" maximizes the expected value of a utility function which depends on damage level in a "step-function" manner. A more realistic utility function would still place great importance on achieving an acceptably large damage level, but would not be discontinuous.

The need for such a utility function underlies the general mistrust of expected-value optimizers. It is clear, for example, that a 45% probability of defense suppression is not in fact half as desirable as a 90% probability of suppression--the former may be worthless to a follow-on attack which assumes no effective surviving defense. On the other hand, to demand 90% probability of defense suppression, and give no preference to 89% suppression over 10% suppression, is obviously to err in the opposite direction.

The explicit selection of a utility function on the damage levels against groups of targets permits a more valid specification of real goals.

A.3 WAYS OF TREATING UNCERTAINTY

A.3.1 Introduction

The purpose of this section is to survey ways to incorporate uncertainty considerations into strategic attack generator and attack assessment models in order to better comprehend the effects of uncertainty on the outcomes.

A.3.2 Shared Failures, Weapon Correlations

A proper treatment of shared failures within and among weapons types leads to a payoff or objective function which, when optimized, involves mixes of different types of weapons (cross-targeting) on a single target. This is in contrast to the usual optimization result that there is a best first weapon assignment for any target (highest single shot kill probability) and more of that weapon is the best multiple weapon assignment (based simply on the compounding of independent probabilities).

When "expected target damage" is predicted in the conventional way, ignoring the uncertainty in the planning factors, then cross-targeting is usually accompanied by a decrease in the predicted "expected target damage." This effect is misleading. It is a consequence of the simplifying assumptions in the calculation. When the target survival probabilities are correctly calculated (including the effects of uncertainty), then the judicious use of cross-targeting can increase the expected target damage as well as the damage assurance. In the new damage assessment system, explicit sampling over the uncertainty range of planning factors results in calculation of an accurate expected value of damage that will indeed improve with appropriate cross targeting.

This can be illustrated in a simple example. Consider weapons of Type A. Each weapon is assumed to have a 90% chance of destroying a target if it is delivered, but all Type A weapons come from the same base, which is assumed to have a 50% chance of being destroyed before any weapons can be launched. The overall single shot kill probability for these weapons is 45%. However, the incremental kill probability for second weapon, given that one is already allocated to the target, is much less. This, of course, reflects the fact that the weapon kill probabilities are not independent. In the model to

be developed here, the lack of independence is a direct result of assumed uncertainty in the probability of DBL. In the preceding example, we can say that the DBL probability for weapons on the base has a 50% probability of being either 1.0 or 0.0. Thus, the reliability itself can be treated as a random variable.

To show quantitatively the effects of this uncertainty, it is helpful to think in terms of the probability of target survival. Specifically, if the two weapons are allocated to the target, and their base survives, then the target survival probability will be $.1 \times .1$ or $.01$. If, on the other hand, their base is destroyed, then the target survival probability is 1.0. Since base survival and base destruction are equally likely, the overall probability of the target surviving both weapons is $(.01 + 1.0)/2$ or $.505$, compared to $.55$ for a single weapon. Thus, the expected incremental value of being destroyed by the second weapon is only $.045$. Dividing this incremental kill by the expected target value left after the first weapon gives $.045/.55$ or $.082$! The conventional "expected target damage" calculation, of course, would continue to use the $.45$ single shot kill probability as the incremental kill probability and consequently in such a case, would substantially overestimate target kill.

The effect can also be explained in terms of conditional probabilities, when the lack of independence is considered. For the first weapon, we can assume a simple 50% probability of DBL. However, when we consider the second weapon, the first weapon either has, or has not, killed the target. If the first weapon killed the target, there is no point in sending a second weapon. If the first weapon failed to kill the target, it might be because the base was destroyed, in which case the second weapon would also fail. Thus, the appropriate probability of DBL for the second weapon, conditioned by the knowledge that the first weapon failed, is higher than 50% and its incremental kill probability is correspondingly reduced.

To demonstrate how these considerations make cross targeting desirable, let us now consider a weapon of a different type, B, which cannot be destroyed before launch, but which has only a 30% probability of destroying the target if it is launched. Table A-1 illustrates expected target kill probabilities for various combinations of weapons of types A and B. Results are shown both for the correct or detailed calculation, and for the conventional simplifying assumption of independent probabilities corresponding to no uncertainty in the DBL probability.

The underlined numbers indicate where the correct calculations differ from the conventional simplified calculations.

Table A-1. Predicted Target Kill Probabilities

<u>Number of Weapons</u>	<u>Weapon Mix</u>	<u>Assuming Independence Between Weapons</u>	<u>Considering Correlation due to DBL Factor for Weapon A</u>
1	Type A	45%	45%
1	Type B	30%	30%
2	Both type A	69.75%	<u>49.5%</u>
2	1 type A 1 type B	61.5%	61.5%
2	Both type B	51%	51%
3	All type A	83.36%	<u>49.95%</u>
3	2 type A 1 type B	78.825%	<u>64.65%</u>
3	1 type A 2 type B	75.25%	75.25%
3	All type B	65.7%	65.7%

It for simplicity we now assume that all of these weapons have equally valuable uses elsewhere in a war plan and that they are in about equal supply, then this table can be used to illustrate a very general result of cross-targeting analysis. Notice that when calculations are done the conventional way, the highest kill probability for any given number of weapons is always achieved by using only the weapon types with the highest single shot kill probability. When the calculations are done this simplified way, cross-targeting or mixing of weapon types never seems desirable because it erroneously appears to reduce the expected target value destroyed. When the calculations are done correctly, the maximum kill probability for multiple weapons requires the mixing of weapon types, to avoid excessive dependence on weapon types that are subject to the same uncertainty in the planning factors. Notice that weapon type B is clearly less cost effective than type A when only one weapon is used. However, because weapon B does not involve uncertainty in the planning factors, multiple weapons of type B are more cost effective than multiple weapons of type A. However, in this example, regardless of the number of weapons allocated, the effectiveness of an unmixed allocation of type B weapons can always be improved by substituting at least one weapon of type A.

In designing a damage assessment system to reflect the effect of shared unreliabilities, the basic approach is to sample from distributions for weapon reliability in such a way as to maintain the proper correlations between reliabilities (or survivabilities, or penetration probabilities) of weapons of the same type, class or geographic region.

A.3.3 Strategic Force Design and Diversity In Weapons Systems

There are eventualities under which certain U.S. weapons systems might fail catastrophically, leading to an "unacceptable" outcome of the war. We desire to detect and react to the opponent's measures

that could lead to such failures of our systems. And we desire to design our force posture to minimize the possibility of such failings that lead to loss of the war. Thus we are led to a dual objective of high expected damage and exceedingly low chance of very small damage. The next section discusses how to derive utility functions to reflect specifically such concern.

Procurement of a diversity of weapons systems is the fundamental hedge against unexpected system-wide failures, such as might result from:

1. An exceedingly well-coordinated preemptive strike against bombers or ICBMs
2. Extraordinary ASW capability against the SLBM force
3. Unanticipated nuclear effects or
4. Significant ABM capability in primarily anti-aircraft defenses.

But, recognizing the need for diversity, we must ask how many different weapons systems are needed, and how force allocations are to be obtained to hedge properly for system unreliabilities.

These questions are addressed in the next section with some examples generated from aggregated models developed to investigate weapon correlation problems in a more responsive way than using detailed systems such as QUICK--which is probably the original framework to include a representation of weapon correlations and thereby induce automatic cross-targeted allocations.

A.3.4 Conservative and Optimistic Targeting

While these topics properly belong in the next section on ways to handle uncertainty, since they deal with changing the way the force is used in order to correct deficiencies when targeting is based on

"sure" values, they also are an intuitive approach to direct inclusion of uncertainty. One can redo an attack plan, assuming some system (or all systems) will perform at the low end of its a priori uncertainty range. This conservative targeting plan is generated with deterministic values of the planning factors and hence doesn't present new methodological problems. Similarly, an optimistic plan can be presented. These can then be evaluated on a conservative, optimistic or other basis. If either performs nearly as well as the original plan, then some statements can be made that the uncertainty can be overcome.

A.3.5 Worst Case Sensitivity Analyses

Any strategic allocation or war plan should be evaluated over a spectrum of parameter values and variations in planning factors. This sensitivity analysis, of course should include worst case examples. An obvious problem with worst case analysis is that often the effectiveness is reduced to zero. Some compromise in choice of "worst case" is usually made on a basis of good judgment. Such parametric analyses are usually the main alternatives for treating uncertainty. The approach taken is inherently a one-at-a-time scan of each factor to test the variability in the payoff function due to variations in each factor (in partial derivative sense). Given many uncertain factors, most-likely values are usually chosen for those held fixed. Obviously, this procedure misses the joint influence of several factors in combination. But, also it does tend to highlight the most important factors, those to which the payoff is most sensitive.

A.3.6 Sampling (Monte Carlo) Approach

A technique built into some simulator executive systems allows any input parameter to be drawn from an uncertainty distribution rather than specified as a deterministic quantity. After completing a number of such sampling experiments, calculating the payoff repeatedly for each set of input variables drawn, a good estimate of the mean

and variance in the outcome is available. This reflects the joint impact of many uncertainties, given good representations of the uncertainty distributions in the first place. Correlations between variables become more difficult to include. The UNCLE model of RAND sets an aggregated strategic exchange representation in a framework like the above. Planning variables have been "preoptimized" and are included in the representation without consideration of uncertainty. These include counterforce and countervalue divisions of force, first strike and withheld divisions of force, etc. Weapon characteristics are drawn from a selection of distribution forms and an expected payoff and its variance, subject to the uncertainties, is obtained. Correlations are treated only in an "ad hoc" manner. No model of correlated failures is inherent in the structure. UNCLE suffers from a lack of acceptability because of the many assumptions and simplifications in the strategic representation demanded by the fast run time essential to this sampling approach.

The damage assessment framework of the original BRISK/FRISK system essentially provides a means to Monte Carlo attack and wind variables, depending on efficient population sampling to develop high accuracy estimates of expected fatalities. In the new system, explicit distributions of outcomes are also developed by extending the original methodology beyond simple means and variances to include distribution information. A capability to sample over planning factor uncertainties is also described, and includes a proper treatment of correlations in the distributions. No such capability existed in BRISK/FRISK.

A.3.7 Incorporation of Uncertainty In The Payoff Function

If the opposite approach to the sampling method were envisioned, the uncertainty would be included in the analytical representation of the payoff function, and any given war plan or allocation could be evaluated directly in a stochastic sense. Thus, if the hardness of a

target were uncertain, a revised damage function could be derived by incorporating a distribution of hardness into the damage function and then integrating over the distribution. The result allows one to examine the effects on specific attacks of the uncertainty postulated and to see how conservative or pessimistic assumptions about nominal hardness affect the attack efficiency.

This method, when feasible, is most powerful and merely extends the usual statistical inclusion of accuracy and lethal distance distributions to other classes of uncertainties.

A.3.8 Multiple Sets of Descriptive Information

A popular treatment of uncertainty tied to perceptions of the opponent's forces and capabilities is provided by the creation of a BLUE viewpoint and RED viewpoint data base, with perhaps a third set of values for the same data describing real capabilities. This allows for many parametric variations, but is subject to argument as too subjective for definitive evaluations. The capability is built into many strategic exchange models, since it basically only adds to the data storage requirements. A capability to generate plans and separately evaluate them is required of the structure as well.

A.3.9 Probabilistic State Space Representations

It is appropriate to visualize the strategic planning, especially the force procurement, problem in terms of a matrix. One dimension includes all the possible (or at least a good selection of the) states of the world. The "state" may be far less encompassing, but is meant to include variations in technology, etc. The other dimension includes the courses of action, or weapon procurement programs, for example, that might be contemplated. The matrix is filled in with effectiveness and cost values indexed by state and program, with the additional factor--the probability a given state will occur--conditioned on that program being

selected. The framework certainly is unassailable compared to best expected, single state based, procurement decisions, but as a direct technique for including consideration of future uncertainty may be beyond practical implementation.

A.3.10 ENVIRONMENTAL UNCERTAINTIES

The most critical factor for assessing population damage is the variability in fallout production and distribution due to soil composition uncertainty, HOB uncertainty, or wind variance, etc. Representation of wind sensitivity by consideration of results for two or three typical day's wind patterns falls somewhat short of the ideal, but is far superior to simply averaging winds and then conducting a single evaluation for an average wind. The approach of generating and storing may representative national wind maps (with proper time and space correlations) and sampling among those, as we recommend for the new system, is conceptually simple and very powerful.

A.4 WAYS OF HEDGING AGAINST UNCERTAINTY

A.4.i Introduction

Implicit in the preceding description of various ways of including uncertainty in strategic analyses is the implied requirement to improve the plan or redesign the force to cope with the uncertainty. Sometimes this is possible. But it must be recognized that even an optimal hedged plan, taking full and proper account of certain types of uncertainty, might well perform inadequately--i.e., no better than a simple, unhedged plan. It may not be obvious when this is the case. Hence, in any case, the subject of constructing hedged strategic plans is a proper element toward introducing the analysis both of the effectiveness of our own plans in producing levels of damage in the face of strategic uncertainties and of the effectiveness of potential enemy attacks in damaging our population and national resources.

A.4.2 Multiple Weapons Systems and Cross-Targeting

A brief discussion of the motivation for cross-targeting may be useful. Basically, what is involved is a particular form of hedging for uncertainties in preparing a war plan. And the test of a good hedged (cross-targeting) plan is good performance when bad contingencies occur. This can be analyzed in a reasonably quantitative way.

It is important to remember that cross-targeting is an outcome of a hedging strategy which attempts to guard against rather large scale failure of parts of the weapon force. The goal is to hedge, not simply to cross-target as such. There are cases when cross-targeting may be inappropriate, or useless. The surprise attack scenarios of RISOP might involve little of this form of hedging, since failure of the SLBM force, or a large fraction thereof, for example, dooms the attack. The situation cannot be retrieved by adding ICBMs or bombers to time-urgent targets the SLBMs were supposed to kill. On the other hand, the less highly tuned retaliatory options need to be designed for very high confidence of significant total effectiveness, giving up even greater damage capability to raise the confidence of acceptable damage capability. Thus, cross-targeting plays a significant role in hedging in the direction of a guarantee of at least some damage to each target no matter what.

The justification for procuring a diversified attack force has been a widespread fear of "putting all the eggs in a single basket"; the possibility that an entire strategic system may fail or be seriously degraded because of an unforeseen contingency. The only way to quantitatively analyze this situation is to explicitly take into consideration the correlations, or the common risks, which are found throughout a single system.

The QUICK program was written partly to satisfy such a need; however, QUICK is not well suited to aggregated exploratory studies. Aggregated models have been designed to treat in an efficient and transparent way those problems which specifically relate to the

evaluation of the need for multiple weapons system, while avoiding the complexities of a detailed, comprehensive allocation model such as QUICK.

Figure A-1 illustrates the results of a typical parametric study. The effectiveness of 1000 weapons against a typical Soviet data base is evaluated for the following cases:

1. All the weapons are of a single type and completely share any risk factors. For example, this could represent 1000 land-based ICBMs that are either completely destroyed or completely survive a pre-emptive attack.
2. The weapons are divided into two groups of 500 weapons; each group shares the risks, however, the two groups either succeed or fail independently. For example, the 1000 weapons could be divided into two distinct and independent groups of 500 each--one group land-based, the other sea-based.
3. Same as in case 2, except the weapons are divided into three independent groups, perhaps ICBM, SLBM and manned bomber types.
4. Same as above except the weapons are divided into 1000 independent groups--i.e., all weapons are independent and no risks are shared.

The results illustrated in Figure A-1 demonstrate that for reasonably high system reliabilities, having two weapons systems yields almost as high an expected return as having 1000 weapons systems. It would appear that if the only consideration were the expected return, the cost of multiple systems may not be justified.

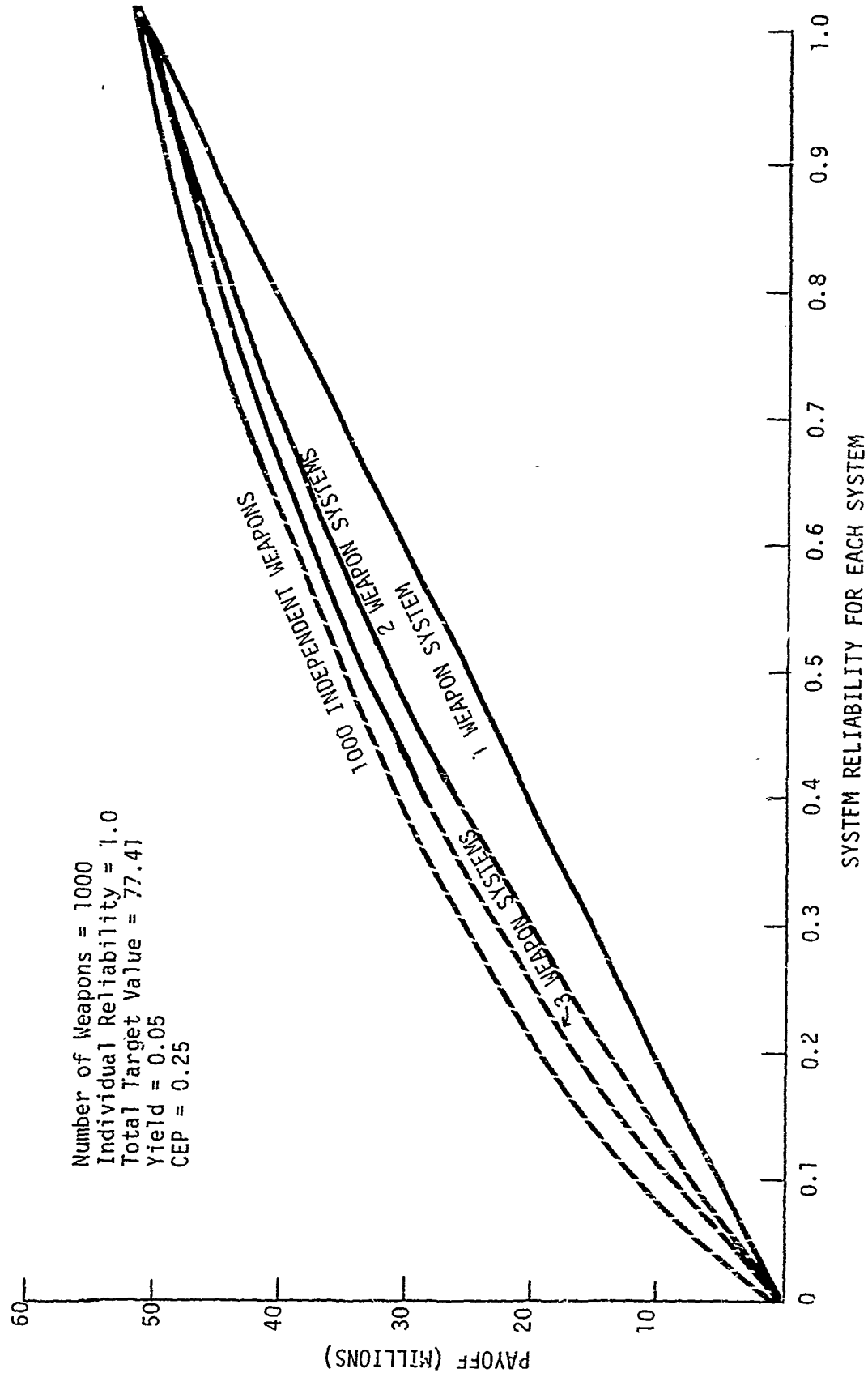


Figure A-1. System Payoff vs. Reliability

However, the experienced military planner usually wants to consider more than expected target destruction. Often the criterion for success is given in terms of probability of achieving some specified level of destruction. If one is interested in assured destruction, the Figure A-1 presents an incomplete picture. Suppose, for example, that one is interested in 50% system reliability--that is, the situation in which each of the missiles are divided into 1000 independent systems, there is a very large probability that approximately one-half the force will survive. If the surviving half is sufficient to satisfy the war objective, then there is a very large probability of "winning the war." However, if the surviving half is not sufficient to satisfy the war objective, there is the same high probability of "not winning the war."

Next consider the case in which the weapons are divided into two systems. The expected return is almost as high; however, there are only three possible situations which can occur:

1. Both systems survive (25% probability)
2. One or the other, but not both, system survives (50% probability)
3. Neither system survives (25% probability).

If one-half the force is sufficient to satisfy the objective, then there is a 75% chance of "winning the war," far below the near certainty for the 1000 system case. Using this criterion, one is led to the conclusion that two systems have nowhere near the value of 1000 systems. However, consider what happens in the situation in which one-half the force is not sufficient to meet the war objective: If there are 1000 systems, failure is almost certain, while if there are only two systems, there still exists a 25% chance of success. In this case the two systems are actually preferred to the 1000 systems.

Both the expected value criterion and the assured destruction criterion can lead the military planner to falacious conclusions. The

expected value criterion implies that the planner is equally satisfied with the following two war plans:

- a. A plan which destroys the entire target system half the time and leaves the entire target system unscathed half the time
- b. A plan which always destroys half the target value.

In reality, most planners would show a strong preference for plan b. On the other hand, we have already shown how the assured destruction criterion can imply a preference for two weapons systems over 1000 systems, even though two systems produce less expected payoff.

Figure A-2 illustrates the utility associated with various payoffs for both the expected value criterion and the assured destruction criterion. The former is linear; the latter, a step function. The "utility" is simply a formalization of "acceptability to the military planner." We have also included (dotted line) a reasonable utility curve reflecting the fact that a small payoff is of little value, that the utility increases rapidly as a critical level is reached, and that very little additional utility is accumulated after the critical level is reached. Such a utility function, while more complex than the linear or step function, reflects a more natural notion of acceptability and alleviates the paradoxes described above.

A.4.3 Game Theory Approach

To cope with deliberate uncertainties, selection of force postures and strategies should be based on two-sided analyses. This naturally leads to derivation of optimal strategies in the game theoretic sense--one side attempting to maximize and the other to minimize some common objective function. Consideration of non-zero sum games is often

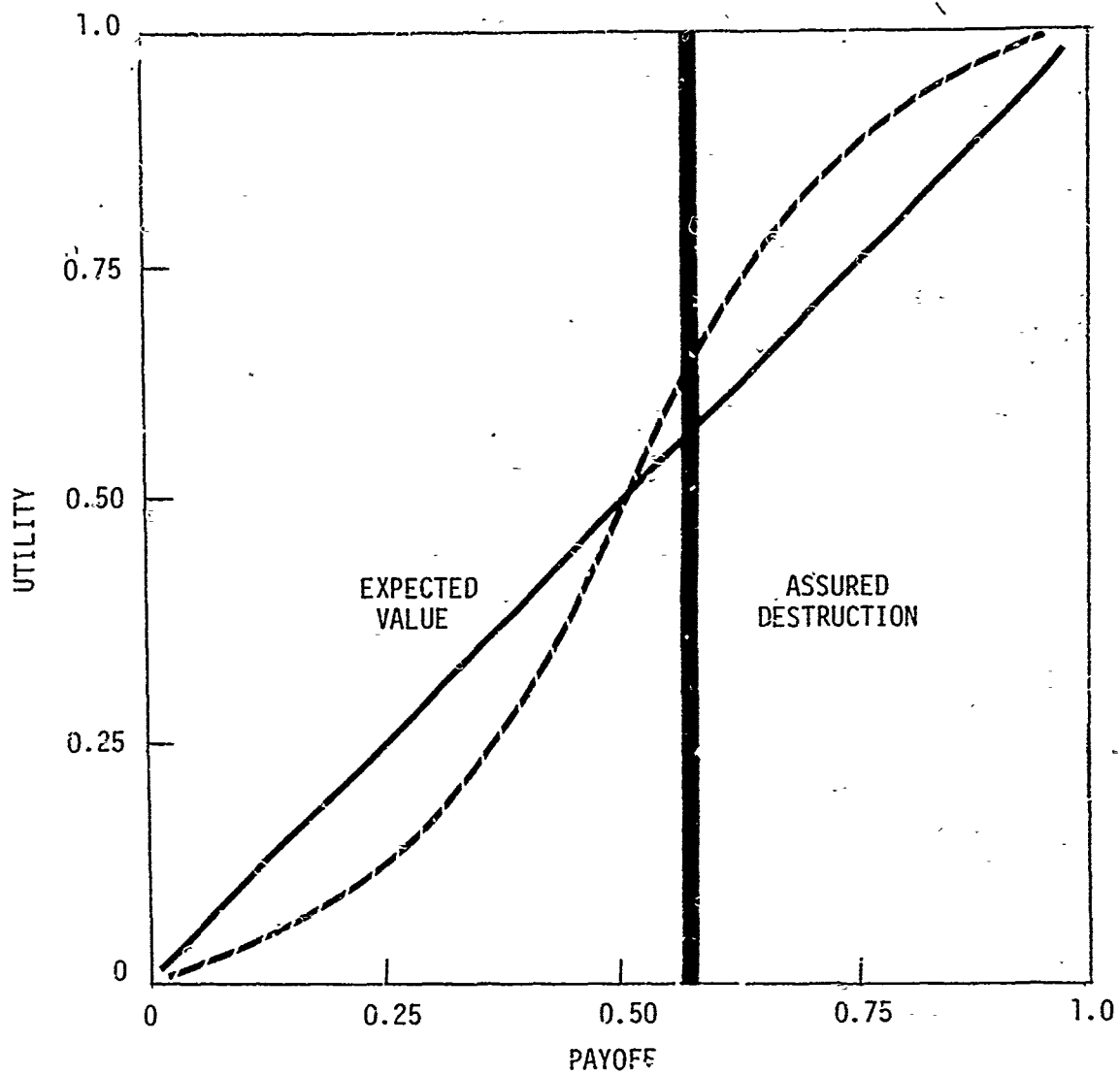


Figure A-2. Utility As A Function of Payoff

attempted (where one side's gain is not the other side's loss), but little light is shed by analysis with such a theoretically ill-behaved branch of game theory.

Work by Pugh and Mayberry (see references) on non-zero sum bargaining or negotiating games makes a plausible case, through Nash's analysis of such games, that the pertinent threat game is a simple zero-sum game in terms of the "losses" to both sides in a threatened engagement, with "losses" interpreted in a broad sense of military, political, economic, etc. This suggests that direct attack on problems by non-zero sum game theory may be unrewarding, while zero sum formulation may be more adequate than often apparent.

A.4.4 Desensitized Strategies

We have discussed various approaches to strategic uncertainty analysis. These begin with the most fundamental--simply to evaluate the tactics of either the offense or defense against situations other than those for which they were designed and optimized. While such a procedure is valuable and sheds considerable light upon the relative sensitivity of tactics to uncertainties, a more sophisticated and satisfactory approach (when it is feasible) is to attempt the direct construction of tactics which deliberately "hedge" against uncertainty and are nearly optimal over a range of circumstances, though not precisely optimal for any single situation. Entirely new techniques must often be employed in the construction of such "desensitized" optimal strategies and tactics, since they do not arise from simple optimization under any particular postulated set of circumstances.

One approach, in which we possess extensive experience, is the utilization of Generalized Lagrange Multiplier (GLM) theory for such applications. The prime value of this technique lies in its ability

to map out optimal solutions for a wide range of resource levels in problems that possess inherently non-linear objective functions. And the generality of the permitted objective functions allows one to incorporate a priori uncertainties in the very measure of effectiveness itself, thus optimizing over the uncertainty range directly, rather than depending on sensitivity or parametric analysis after the fact for heuristic adjustment of narrowly optimal strategies.

Often an optimal solution may be very unstable with respect to changes in the assumptions upon which the solution was based. What is always desirable are desensitized solutions involving hedged strategies that may not necessarily be optimal at any set of conditions but perform relatively well over as broad a range of circumstances as possible. Such strategies are not deductible from standard optimization techniques, nor from sensitivity studies with the usual models; instead they must be derived by inclusion of the proper uncertainties in the initial objective function addressed by the optimization program.

One very good example of a desensitized strategy arose in a study of population and industrial targeting. Optimization for population damage led to B3Z's that led to relatively low industrial damage. And, optimization for industrial damage sacrificed some population damage in the selected aim points. But, changing the objective function to a 50-50 mix of population and industrial damage led to aim points that matched the best industrial damage results and gave up very little population damage. The key seems to be simply inclusion in the payoff function of both objectives, even though the weighting may be quite arbitrary.

At the opposite pole, in a sense, is a result from a dummy terminal interceptor study. It turns out that a concealed terminal

deployment--real interceptors hidden among an equal number of dummy interceptors--can be optimally deployed in a game theoretic sense in precisely the same manner as randomly preallocated area interceptors. The optimal randomized attack strategy in response can also be derived. However, the strategy of counting real and dummy interceptors, assuming all are real, and allocating accordingly, leads to virtually the same payoff. The deception is such a powerful tactic that the optimal hedged strategy is barely better than the most simple-minded deterministic response.

Areas where desensitized strategies have been developed successfully in our experience include:

- Hedging for uncertain DBL or weapon reliability in DGZ selection

- Hedging for uncertain decoy performance

- Population vs. industrial targeting

- Cross-targeting

- Day vs. night population distributions

- Uncertain target hardness

- Uncertain attack size against a terminal defense

- Uncertain attack size against an area defense

- Uncertain terminal defense size via dummy interceptors.

A.4.5 Multiple Objectives, Trade-Off Analysis

Among uncertainties in strategic analysis are the values to be placed on multiple, perhaps conflicting, objectives. Trade-off analysis attempts to resolve such uncertainties by an explicit presentation of

what can be accomplished toward one objective in terms of some penalty, or reduced accomplishment, of another. For example, a required level of achievement of one objective is stated, and the second objective is maximized under the constraint. Variation of the constraint and re-optimization of the remaining objective lends useful trade-off information.

A direct treatment of multiple objectives is sometimes possible (GLM lends itself to this, as noted earlier), by incorporation into the payoff function of both objectives--as, for example, a linear combination. Uncertainty in relative weightings always remains with any such combination technique.

Equivalently, in a dual criteria targeting (maximize military damage and minimize civilian damage) analysis, a correspondence between treatment as a constraint and inclusion in the payoff function has been shown. Recall that a resource-constrained optimization process can be transformed into a related process without constraints, but with a new objective function that adds a term containing the resource times a Lagrange Multiplier. Clearly this is equivalent to an original formulation that used a convex combination as the payoff and varied a weighting factor (the Lagrange Multiplier in effect) until the optimal result used the prespecified amount of the constrained resource.

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